

Preliminary Geophysical Characterization Of Two Oil Production Sites, Osage County, Oklahoma – Osage Skiatook Petroleum Environmental Research Project

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ABSTRACT

Ground electromagnetic (EM) and dc resistivity geophysical surveys were used to interpret the subsurface distribution of salinized soil, water, and bedrock at two oil production sites (A and B) on Skiatook Lake in southeastern Osage County, Oklahoma and to characterize the larger scale geologic and hydrologic setting. EM measurements were made on grids of about 1000 m² using a very shallow penetrating (less than 10 m) electromagnetic geophysical system (EM31). At site A, high subsurface conductivities (more than 100 millisiemens/meter, mS/m) found immediately down slope from disposal ponds extended down the local drainage to below the normal pool elevation 231 m (714 ft) of nearby Lake Skiatook. At site B, three areas of high subsurface electrical conductivity were clearly associated with three salt scars and extended in the subsurface below the normal level of Skiatook Lake. DC resistivity soundings were made in and around the two sites in order to characterize deeper (30-60 m) electrical properties of the subsurface lithology and ground water. These soundings and borehole electrical logs show that the shale that dominates the local lithology is moderately resistive (20 to 100 ohm meters). The shale is clearly distinguishable from sandstone interbeds of higher resistivity and saline water bearing horizons of much lower resistivity.

INTRODUCTION

Ground geophysical surveys were done at the Osage Skiatook Petroleum Environmental Research project (OSPER) sites A and B in late September of 2001. Otton and Zielinski (1) describe the location, geologic setting, and oil production history of the study area. The near surface lithology at site A is sandstone, mudstone, clayey sandstone, and shale, at site B it is mostly shale with minor siltstone and sandstone. Surface salt scars caused by release of salt water as part of past oil production activities are present at both areas. Oil production at both sites has occurred since the beginning of the twentieth century, but currently only site B is still producing. Geophysical work for the OSPER project has focused on the characterization and mapping of the subsurface geology and hydrology at each site and the surrounding area. Electrical geophysical logging has been done in two core drill holes at site B.

Methods

Both electromagnetic (EM) induction and galvanic dc resistivity survey methods were used at each site. Though each of these methods is very effective in subsurface mapping, both were affected to varying degrees by conductive metal, primarily tanks and flow lines from production operations. Electrical properties of rocks can be measured in resistivity (ohm meter) or conductivity (siemens). The latter quantity should not be confused with conductance measurements of water, which are commonly expressed in microsiemens/cm ($\mu\text{S}/\text{cm}$), and are not a measure of the volume electrical conductivity but the point-to-point conductivity. Normal borehole geophysical resistivity logs are commonly expressed in ohm meters. Geophysical terrain conductivity systems commonly measure millisiemens, which can be related to ohm meters as:

$$1 \text{ ohm meter} = 1/1000 \text{ millisiemens.}$$

In sedimentary rock, the bulk electrical conductivity is controlled by the porosity and conductance of the pore fluid. A porous rock containing water with a high conductance will also have a high electrical conductivity or a low resistivity. Thus electrical geophysical methods are popular in mapping plumes of saline water (2). Other earth materials such as clays, siltstones, and shales can have high electrical conductivities.

Therefore, high electrical conductivity is not uniquely correlated with poor water quality (high total dissolved solids, TDS).

DC resistivity sounding methods are commonly used in ground water exploration and characterization (2). An electrical current is applied directly into the ground through electrodes and the resulting voltage is measured with a second set of collinear electrodes. We used a Schlumberger array where current electrodes were expanded from less than 1 meter to a maximum spacing of about 100m. Shorter current spacing was used when pipes and other metal objects interfered with larger spacings. Borehole logging contracted to Century Geophysics at site B used a “normal resistivity” method, which also induces a direct current into the earth.

The electromagnetic (EM) induction method uses a wire loop as a transmitter and another loop as a receiver. The electromagnetic field in the transmitter induces a current to flow in the earth (in proportion to the electrical conductivity) that creates a secondary electromagnetic field that is detected by the receiver. We used an EM31 system¹ that has loops separated by 3.1 m. McNeill (3) discusses the principles of this geophysical system. In the normal surveying geometry the transmitter and receiver loops are horizontal coplanar (vertical magnetic dipole, VMD) According to McNeill (4), measurements with this coil configuration have a depth of exploration to about 4.5m. The measurement system can be rotated so the coil system is vertical coplanar (horizontal magnetic dipole, HMD), in which case the depth of exploration is about 2.3m.

GEOPHYSICAL SURVEYS AT SITE A

DC Resistivity Soundings

The location of four dc resistivity soundings made at the site is shown in Figure 1. Sounding number seven is located at the south end of the prominent salt scar discussed by Otton and Zielinski (1). The digitized field measured apparent resistivities, interpreted subsurface layer resistivities, and computed apparent resistivities for sounding 7 are shown in Figure 2. Note that the x-axis of Figure 2 represents both the distance between current electrodes for the measurement of apparent resistivity and depth of the layered

¹ Use of particular manufacturers and instruments does not directly or indirectly imply endorsement by the U.S. Geological Survey

earth in meters. The y-axis represents both the observed apparent resistivity and the interpreted layer resistivity. Sounding number 7 shows layers of very low resistivity, less than 10 ohm meters (100 mS/m). This interpreted low resistivity (high conductivity) zone from 1.5 to 8 m is due to saline waters that have caused the salt scarring rather than the presence of conductive clays. This interpreted subsurface zone correlates with high conductivities mapped in the EM31 survey. The interpreted low resistivities do not extend to depth suggesting that the saline waters have not come from a source at depth directly beneath the sounding. This interpretation agrees well with nearby auger drill holes AA04 and AA02 which identified saline water in sandstone at depths of 1.5 to 8 m.

The interpreted subsurface conductivities from the dc resistivity soundings are shown as a cross section in Figure 3. The edge of the saline water layer is interpolated between soundings 7 and 8 to the east. There is a pronounced decrease in interpreted subsurface conductivity for sounding 9 in comparison to sounding 6. One possible interpretation is that westward extension of high subsurface conductivity in the sandstone is terminated at a fault contact with relatively less permeable shale.

EM31 Survey

The survey grid was constructed using measuring tape and compass. Points on the grid were tied to survey points used for geologic mapping (1). A surveying GPS system with better than .1 m accuracy (5) was used to geographically position the geophysical survey grid. Survey lines were measured North-South every 10 m along an East-West baseline. A few fill-in lines were surveyed at 5 m. Stations along the lines were measured every 1 m. Apparent conductivity measurements were made with both the vertical and horizontal magnetic dipole (VMD and HMD) configuration. Figure 4 shows the conductivities for the VMD configuration (4.5 m). Results from the shallower (2.5 m) HMD configuration are not shown since the map because survey results are much the same. This result is consistent with the 1.5 to 8 m depth of saline water observed in auger drill holes.

High measured conductivities from 100 mS to nearly 200 mS are located entirely north of the East-West road through the middle of site A. The conductivity highs are undoubtedly the result of shallow saline waters, which probably contributed salts to the area of the salt scar. Probably sources of the saline water are the impoundment ponds

located immediately south of the road (Figure 4). High conductivities are located further to the northwest than might be expected if these ponds were the only source of saline waters. Older temporary impoundment areas may also have been located further to the north during past oil production.

The high subsurface conductivities shown in Figure 4 end before the drainage enters Skiatook Lake. One shallow (1.6m) well near the lakeshore contains saline water of 12,000 TDS (6). This well is located at the terminus of the salt-scarred area and probably receives salts originated from the high conductivity, presumably contaminated area indicated in Figure 4.

GEOPHYSICAL SURVEYS AT SITE B

DC Resistivity Survey

DC soundings were made along a 3km long E-W line that included site B (Figure 5). Sounding #1 is located near a 76 m (260 ft) rotary drill hole (BR01) that was designed to define the lithology above Site B and to evaluate the dc sounding that was done before the drilling. The first 10 m of the hole is weathered sandstone that measured about 500 ohm meters (2 mS) on the normal resistivity geophysical borehole logs. From 10 m to about 30 m, the lithology is predominantly sandstone of resistivity that varies from 50 to 100 ohm meters (20 to 10 mS). The natural gamma logs show some clay rich zones less than 2 m thick within the sandstone that have low neutron porosity and resistivities of about 50 ohm meters (20 mS). Shale occurs below the sandstone to the bottom of the hole where there is a small “marker sandstone” less than 2 m thick. Neutron porosity of the shale is much lower than the sandstone indicating that the shale is very tight and not a good aquifer. The actual formation resistivities cannot be accurately interpreted from these logs since a caliper log was not done. The sandstone portion of the drill holes are more likely to wash out which can have unpredictable effects on the normal resistivity log measurements.

Interpreted subsurface resistivities for DC sounding #1 (Figure 6A) are similar to the resistivity values (100 ohm meter) of the normal borehole log. Plotting conventions for Figure 6 are the same as discussed for Figure 2. The high resistivity weathered zone

(1 – 10 m) has interpreted resistivities of 1000 ohm meters with a thickness of a few meters. The apparent sandstone unit thickness of 30 m agrees well with the observed lithology in the nearby drill hole but the last 20 m a lower resistivity than the upper part of the underlying shale. The lower resistivity may be due to brackish ground water within the sandstone unit. BR01 is screened at 15 –18 m (45-55 ft) where no water has been observed. The well is also screened at 26-31 m (80 – 95 ft) where the waters had a TDS of around 2,000 mg/l but increased in June of 2002 to 9,000 TDS (Y. Kharaka, written communication, 2002).

The interpreted dc resistivity soundings were used to construct an electrical cross section through the locations shown in Figure 5. The cross section (fig. 7) shows that the plateau above the study site that is underlain by shale. Some surficial sandstone aquifers in this area may have brackish water particularly near sounding 3 (Figure 5 and 6B). Near sounding number 12 (fig. 7) there is a thin electrically low resistivity (10 ohm meters) unit close to the surface that may be a localized clay layer that is less than 4 m thick. This layer, if present beneath sounding number 1, is not thick enough to be detected.

DC soundings 13, 10, and 5 were made at the lake edge in October 2001, when the lake was about 1.8 m (6 ft) below the normal pool elevation. Both the sounding near study site B (numbers 5 and 10) and away from the site (number 13) show that at the lake edge there is a subsurface shallow high conductive zone (fig. 7). This could be caused by shallow brackish water in the formation at lake level. At this time the interaction between lake water and ground water has not been studied, but additional electrical studies could shed light on this relationship.

DC sounding number 11 was made near geoprobe hole BE04 (a direct push probe) located on one of the salt scars at site B (1). The interpreted sounding (Figure 8) shows that there is a near surface zone of extremely low resistivity less than 3 ohm meters (330 mS/m) at 0.6 – 2.0 m depth. The low resistivity (high conductivity) is caused by saline water that is observed in this and other shallow wells borehole. The saline waters are only 1-2 m thick, suggesting that the shale bedrock acts as an effective confining layer, and that the saline waters have not penetrated the shale.

EM31 SURVEY

Ground conductivity measurements were made at 1 m intervals along grid lines trending northwest-southeast and spaced 10 m apart. Measurements were made with both vertical magnetic dipole (VMD, 5.5 m depth of exploration) and horizontal magnetic dipole (HMD, 2.25 m depth of exploration) orientations. Figure 9 shows the conductivity map for the horizontal magnetic dipole. The northwestern most salt scar (Figure 9) does not have an associated area of high subsurface conductivity. The conductive anomaly in this area is caused by metal pipes. This area of the oil production facility also is the location of a salt water injection well (1) for the complex.

The middle salt scar (Figure 9) has a subsurface conductivity high that is slightly offset from the center of the scar. The area of very saline shallow water is near geoprobe hole BE04, discussed previously. The zone of saline water trends northeast toward the creek and lake shore. At the time the ground survey was done, the lake level was below normal. It does not appear that the very high salinity plume would extend under the lake. However, it should be noted that high conductivities occur along the stream channel, which is normally below lake level.

The southeastern salt scar (Figure 9) is down slope from an active pit (shown in gray) that temporarily stores both brine and hydrocarbons from the adjacent tank battery. The salt scar is likely due to brines in this pit. Very high concentrations of salt are found in the colluvium just southeast of the berm around the pit, and at times, very high TDS (several thousand mg/l) have been observed at the base of the berm. The highest subsurface conductivity associated with the southeastern salt scar was measured in an area that is normally submerged when the lake is at normal level. .

Figure 10 shows the VMD conductivity data (5.5 m depth of penetration) and geologic features superimposed on a 1960 aerial photograph that was geographically registered (5) to the survey area. There are two areas (indicated by “1” and “2” in Figure 10) at the southeast part of site B that were associated with oil production in 1960 was taken, but are now below the normal lake level. In February of 2002 the lake level was still low and exposed parts of the two areas. A relic portion of a berm was noted at the circular feature labeled “1” (Figure 10). One possible interpretation of the circular features on the photograph is that the darker area (“2” in Figure 10) was a holding pond

for hydrocarbons. The lighter feature (“1” in Figure 10) may have been a holding pond for brine. If this is the case then the much higher conductivities in this area might be a remnant plume from this storage area. The berm may have also served to retard the flow of more recent brine release from the existing storage pit.

CONCLUSIONS

Schlumberger dc resistivity soundings show that shales and sandstones at the two study sites have moderately high electrical conductivity ranging from 20-100 mS/m (10-50 ohm meters). Generally shales have a lower electrical conductivity than sandstones due to higher clay content (3). Shale in this geologic setting has low primary permeability, suggesting that ground-water flow in this unit probably is fracture controlled. Borehole resistivity and natural gamma logs support this interpretation. DC soundings on the hill above site B suggest that local sandstone aquifers carry brackish water but do not indicate highly saline waters. The lack of highly conductive clays in the geologic section reduces the likelihood that they are the source of high measured conductivity. Areas of very high conductivity, more than 100 mS/m are likely to be caused by saline waters.

DC soundings completed near the lakeshore indicate very shallow (less than a meter) highly conductive (perhaps as high as 150 mS/m) layers near site B and several km away from the contamination. Since the shallow high conductivity is at lake level, there is a strong possibility that the lake water, ground water, and sediments are interacting to cause the high conductivity zone. Additional studies are needed to map shallow ground-water near the lake shore.

EM31 ground conductivity surveys at both sites suggest that saline waters associated with salt scars have a more complex subsurface distribution than the scar exposures suggest at Site B. The saline waters are confined to the upper few meters of colluvium. At site B, saline waters do not appear to significantly penetrate the shale bedrock and are confined to the colluvial cover. At site A, saline waters are also confined to within a few meters of the surface, however the shallow bedrock is porous sandstone. At site B, saline ground-water is present at shallow depth including areas that are

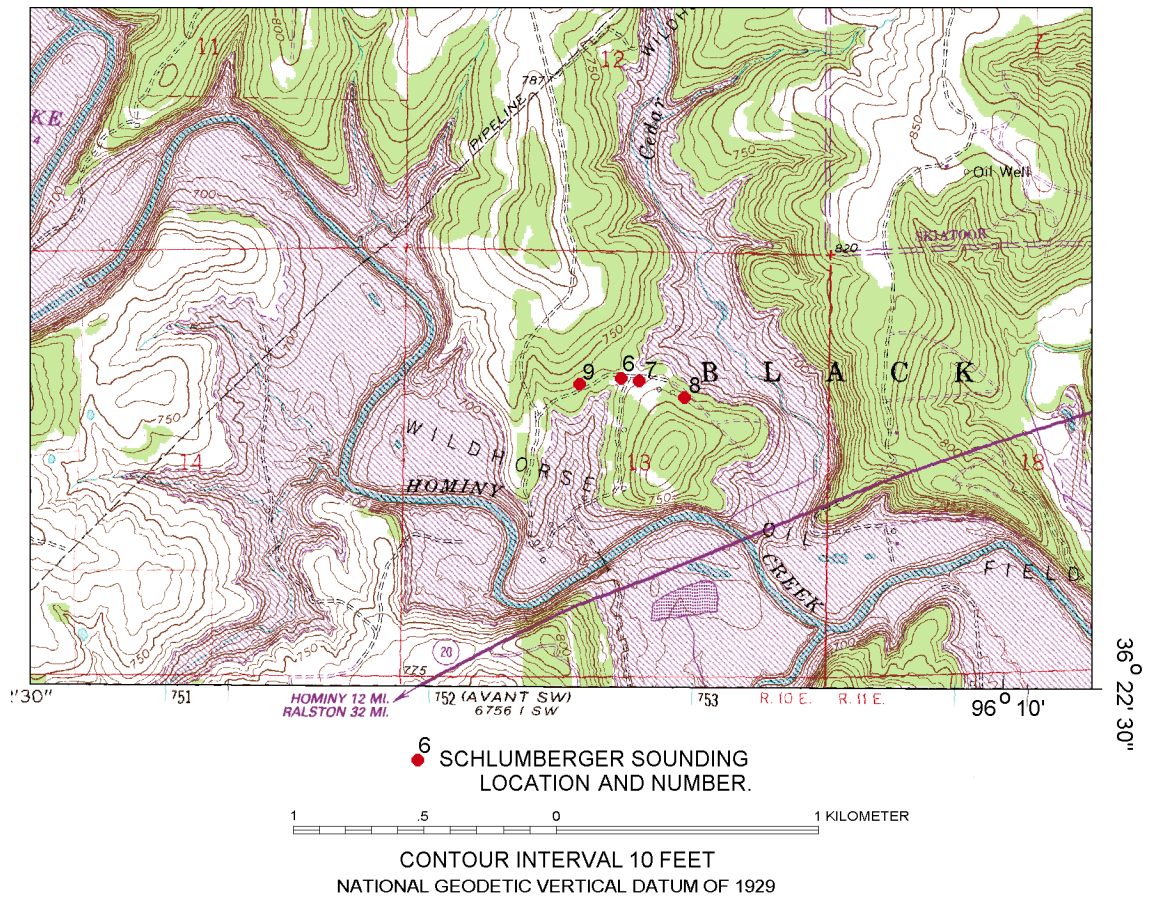
normally submerged by the lake. All of these observations suggest that saline solutions have a high residency time in the near surface lithology even under high recharge conditions.

Subsurface contamination from oil production practices is not always obvious. At site A, surficial hydrocarbons occur as tars from past spills and storage. Yet the geophysical data do not show that large volumes of saline water immediately below these areas. Release of saline waters down the hydraulic gradient from the surface tar has caused the local salt scar. There are several salt scars at site B, but only one scar appears to have a large enough volume of saline water to cause high ground conductivity.

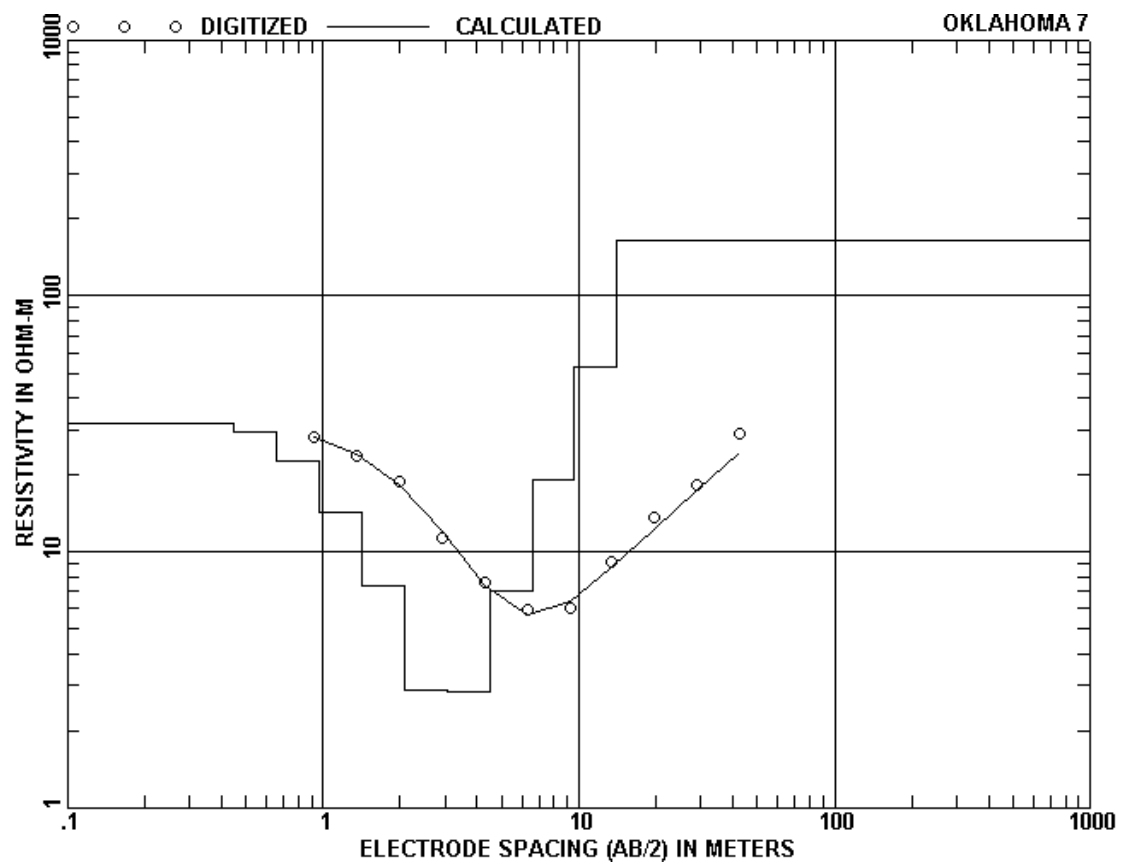
Geophysical ground conductivity measurements have defined specific locations of subsurface saline water at both sites. These conductivity maps could be used in designing remediation methods could .

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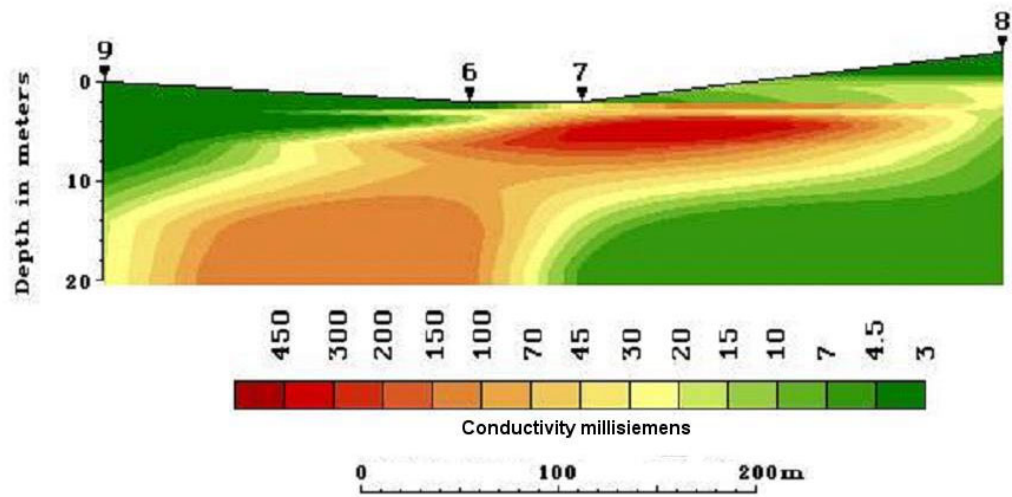
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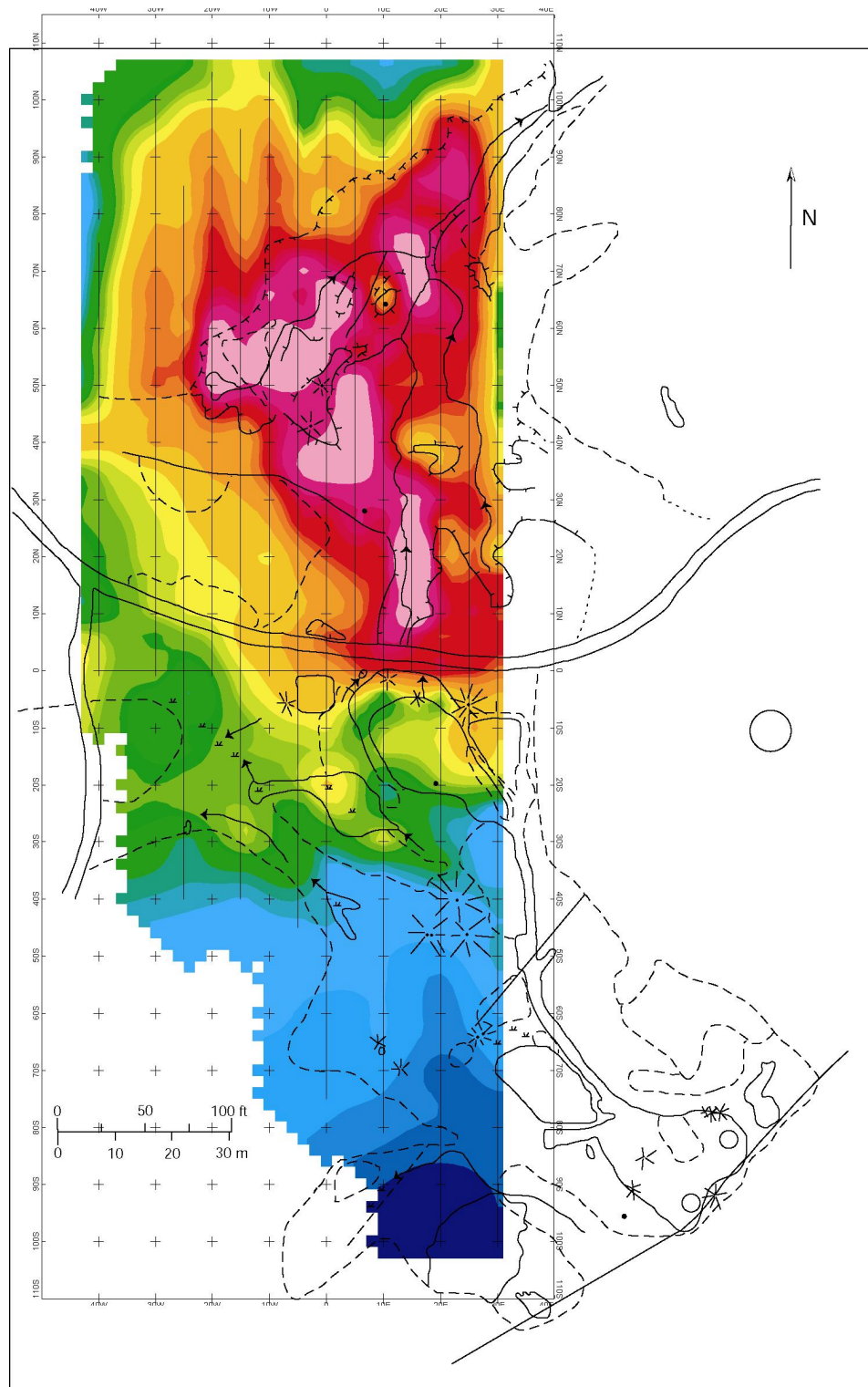
1. Location map of Schlumberger dc soundings at OSPER study site A Figure 1 of Otten and Zielinski (1) gives the general location of study areas. .

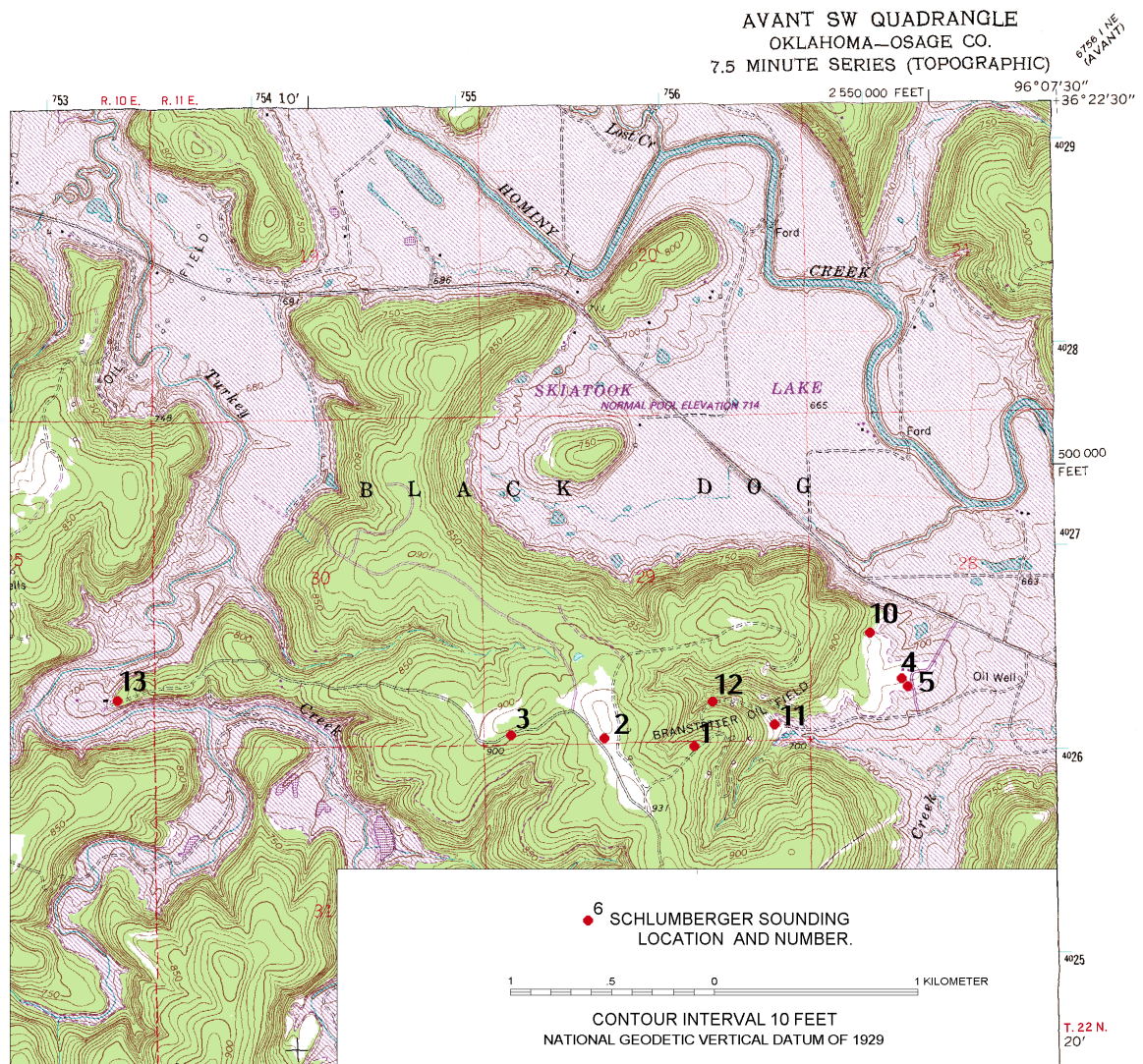


resistivity model as a function of depth that produces the best-fit theoretical solution (smooth solid line).

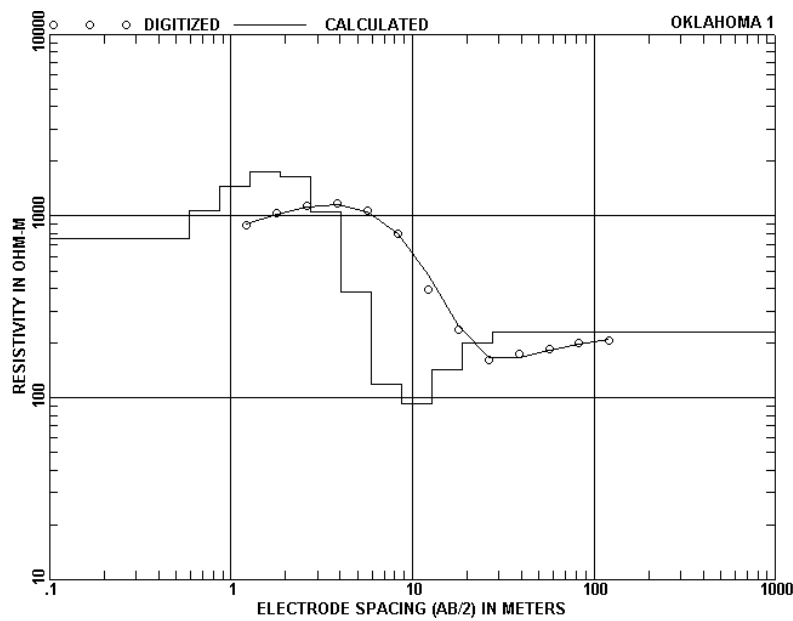
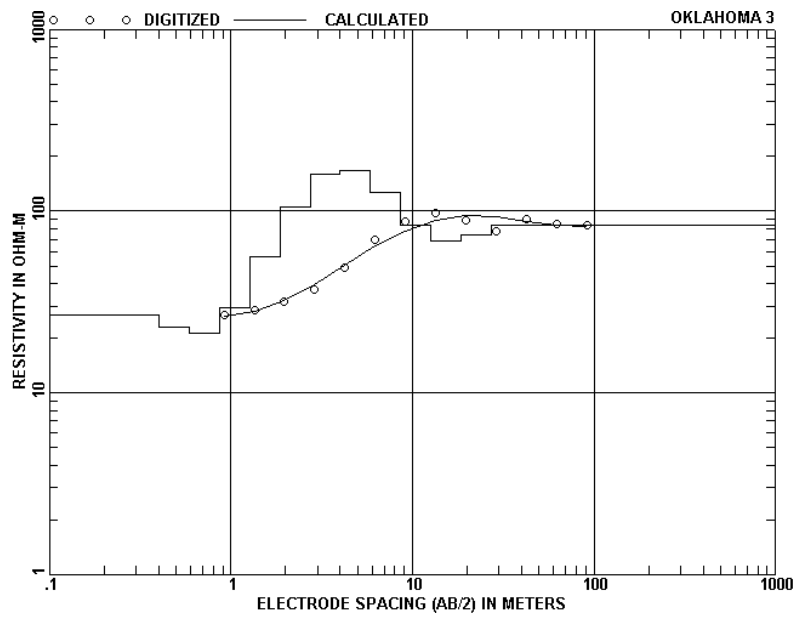


3. Electrical cross section from interpreted Schlumberger dc soundings at site A shown as conductivity in millisiemens per meter.



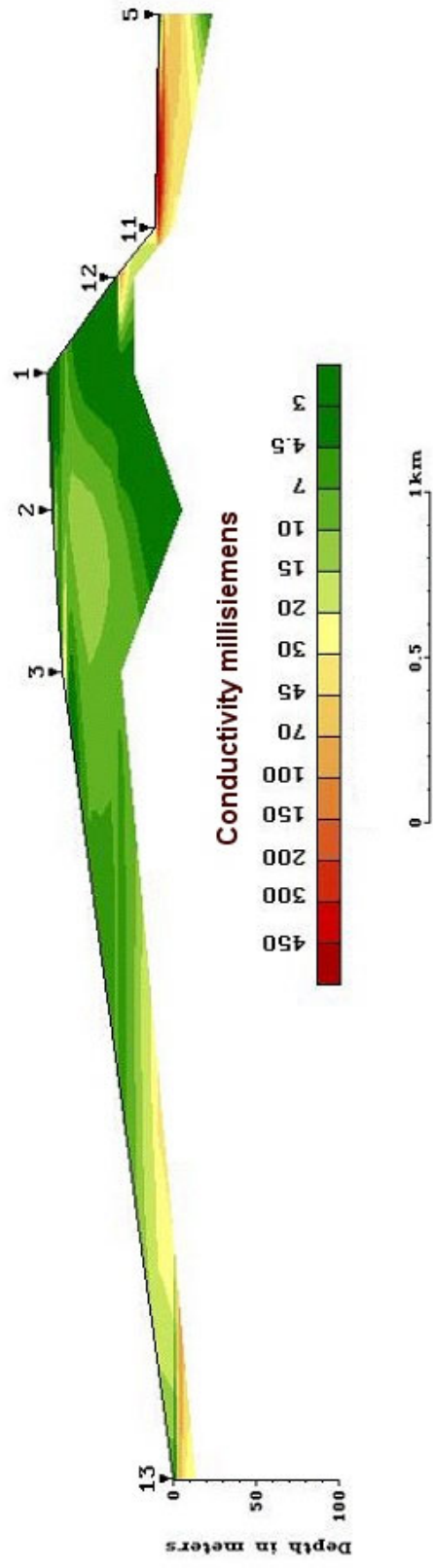


5. Location map of Schlumberger dc soundings at OSPER study site B. Figure 1 of Otten and Zielinski (1) gives the general location of study areas. Sounding number 11 is at study site B.

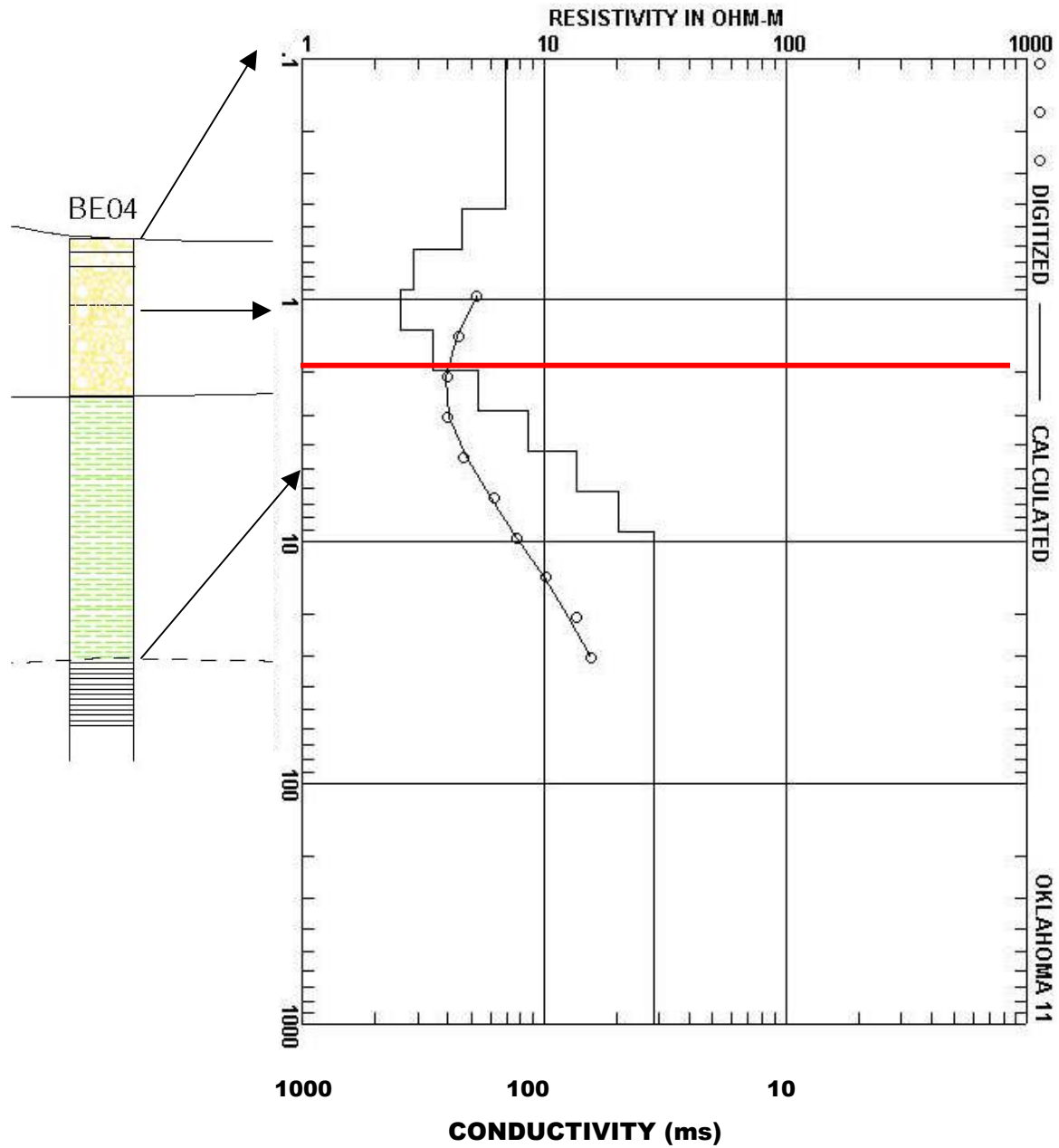


6. Plots c
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indicate digitized field observations. The solid line that resembles a stair step is the
layered earth resistivity model as a function of depth that produces the best-fit theoretical
solution (smooth solid line).

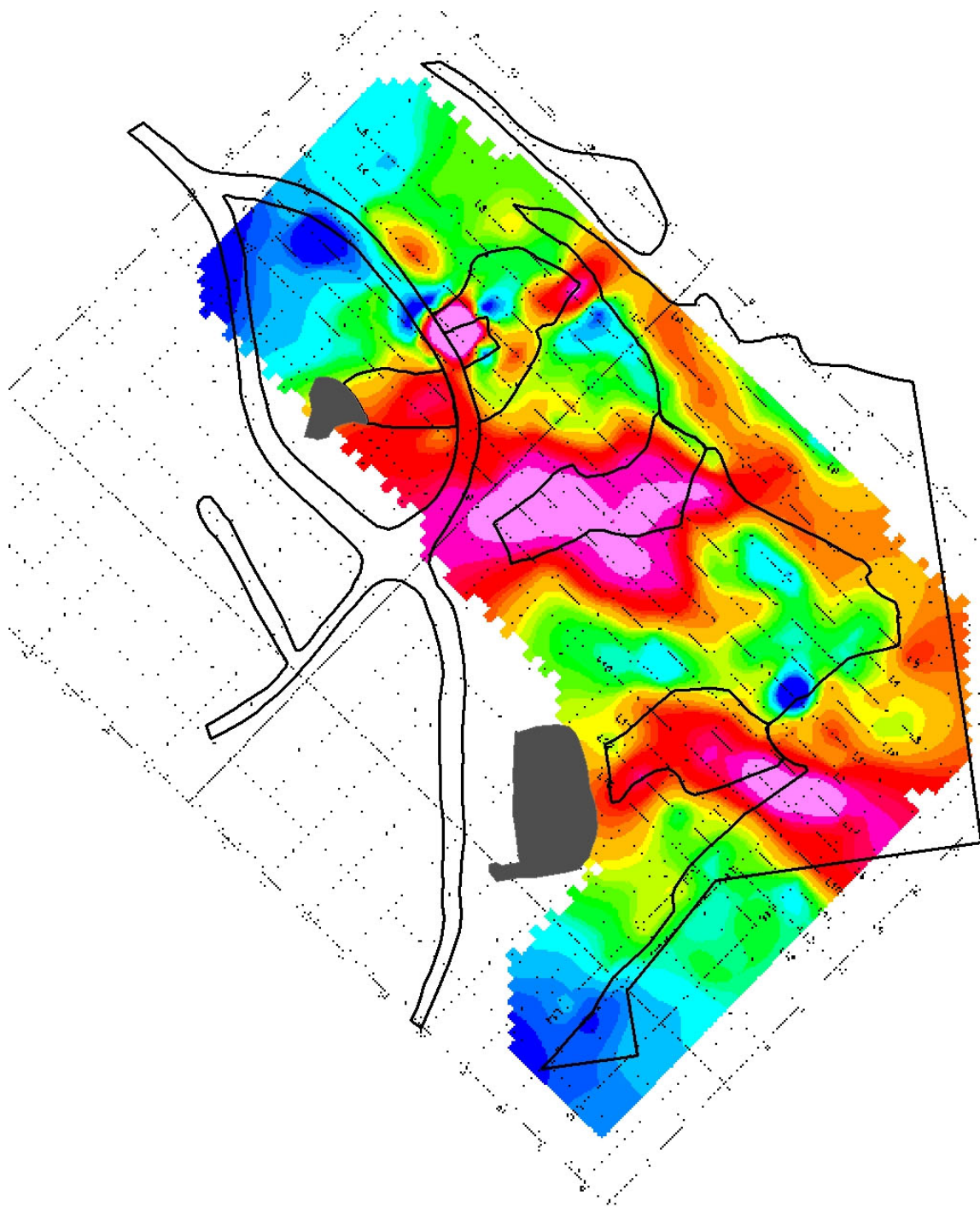
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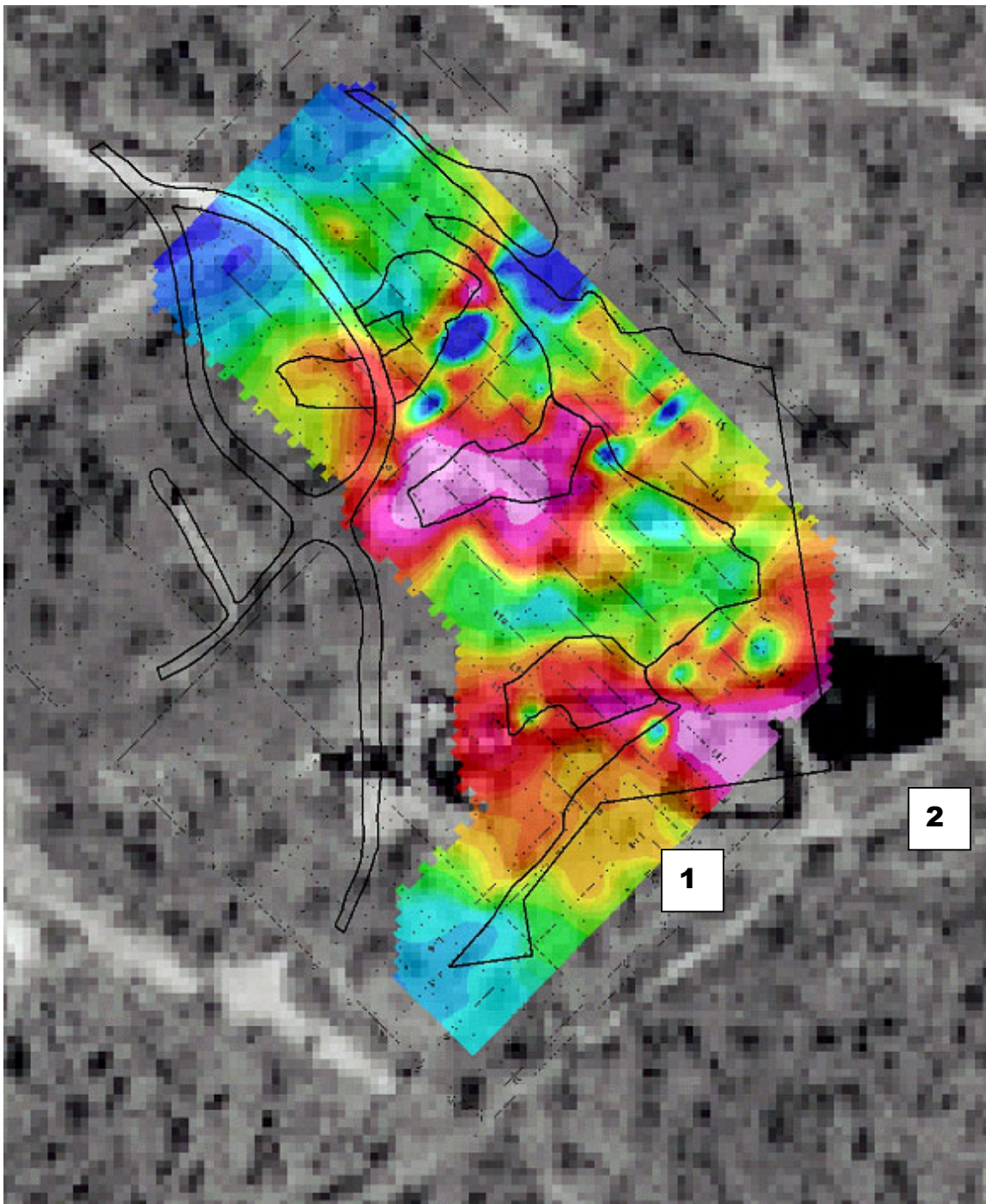
7. Electrical cross section from interpreted Schlumberger dc soundings (see Figure 5) shown as conductivity in millisiemens per meter. Sounding number 11 is at site B



8. DC resistivity sounding number 11 and geoprobe borehole lithologic log. Otton and Zielinski (1) for a description of lithologies. Yellow is colluvium, green is weathered bedrock, and gray is fresh shale bedrock



9. EM31 conductivity map for the horizontal magnetic dipole (2.25 m depth of penetration) of site B at the OSPER study area. The dotted lines show the 10m survey grid. Features on the map are from the site geologic map (1). High conductivities are shown in the warmer colors (red and pink) and low conductivities are shown in cooler colors (green and blue).



10. EM31 conductivity map for the vertical magnetic dipole (5.5 m depth of penetration) of site B at the OSPER study area superimposed on 1960 aerial photograph . The dotted lines show the 10m survey grid. Features on the map are from the site geologic map (1). High conductivities are shown in the warmer colors (red and pink) and low conductivities are shown in cooler colors (green and blue). Areas marked 1 and 2 are likely man-made features associated with past oil production. The darker area (marked 2) is likely a hydrocarbon storage pond and the lighter area (marked 1) is likely a brine storage pond.